ITER disruption mitigation
workshop report, main issues, and next steps

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ITER Organization

Disclaimer:

ITER is the Nuclear Facility INB no. 174. This presentation explores physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

IO workshop on Disruption Mitigation in ITER

The workshop took place in March 2017 at IO with 24 external experts.

Workshop Aims

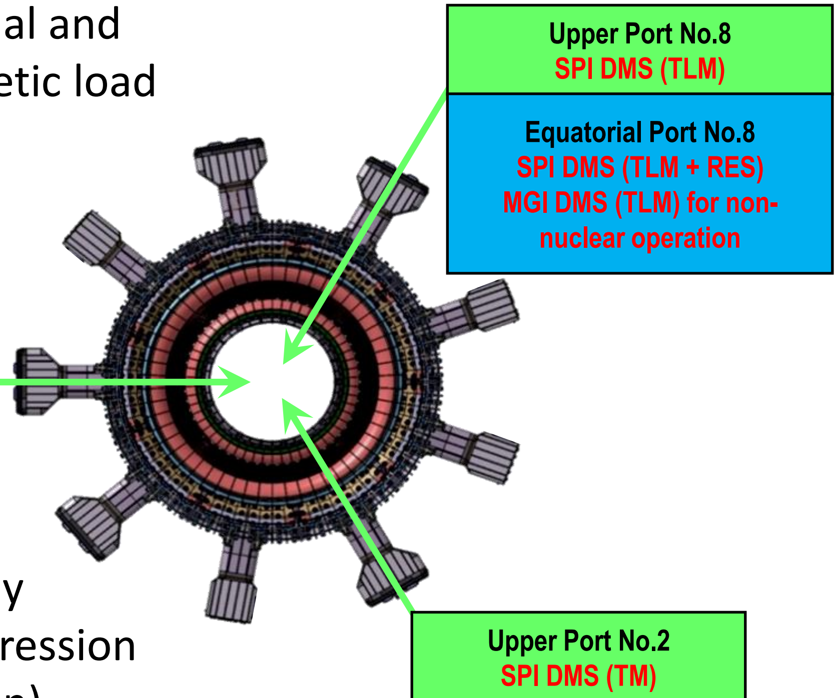
- Review the present understanding of the relevant physics and identify R&D needs to address gaps;
- Discuss the current conceptual and design status of the ITER DMS and, if possible, confirm the present approach, or identify issues that need to be addressed through near term R&D;
- Discuss the approach towards possible alternative concepts, or identify possible mitigation concepts that can be applied in addition to the baseline concept.

The workshop report has been written together with the participants and can be downloaded here:

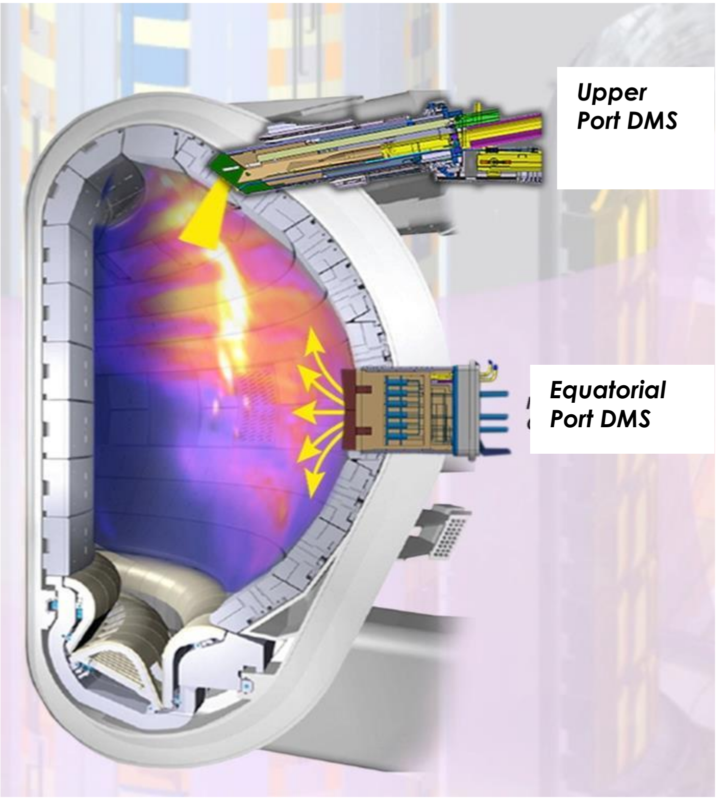
https://user.iter.org/filesharing/FileInfo.aspx?uid=7ad0f9d8-45d9-4bf0-a3cc-6b64e2162117

Present DMS set-up

TLM = Thermal and electromagnetic load mitigation



RES = Runaway electron suppression (and mitigation)

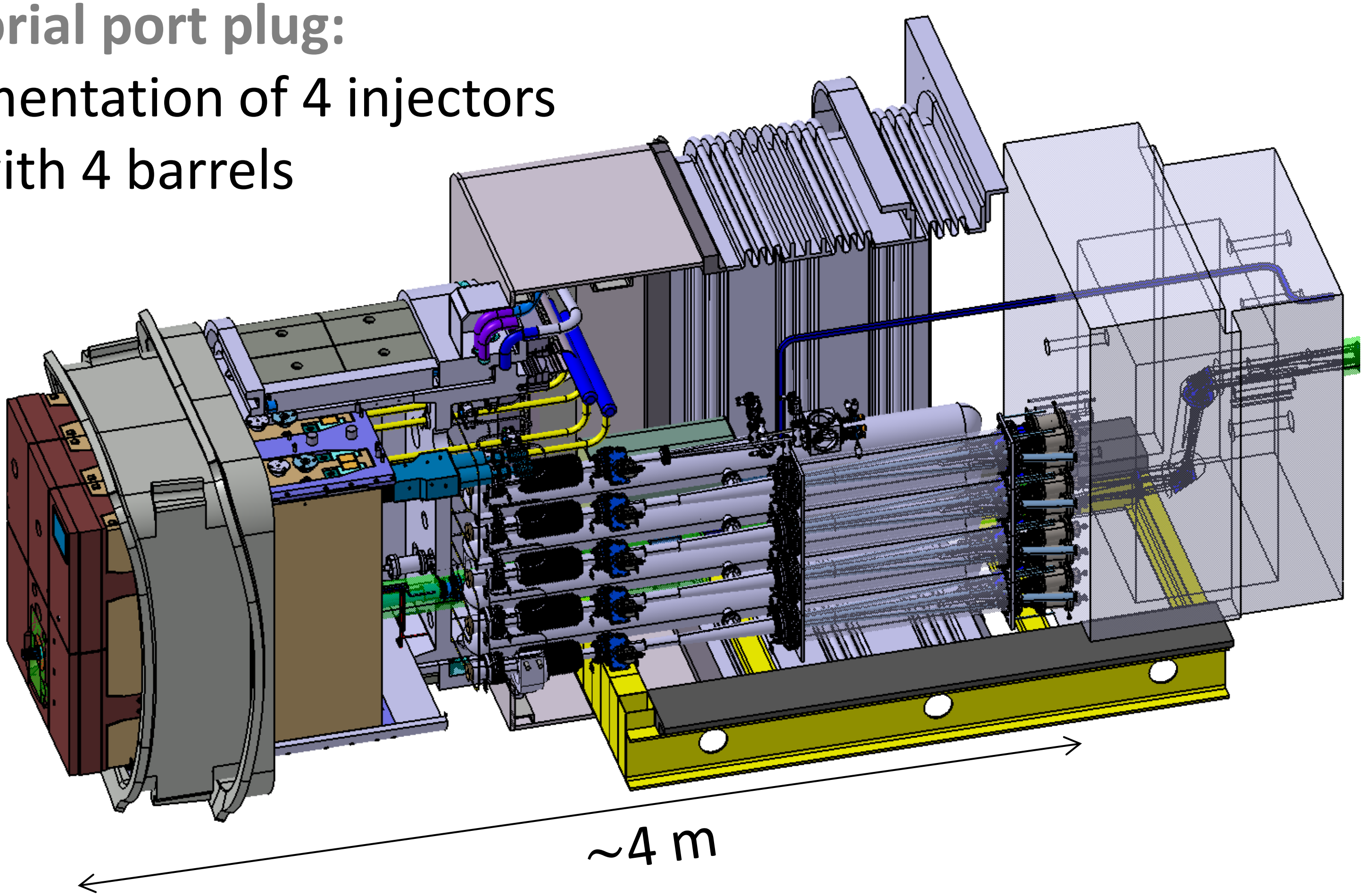


Implementation in ITER

Equatorial port plug:

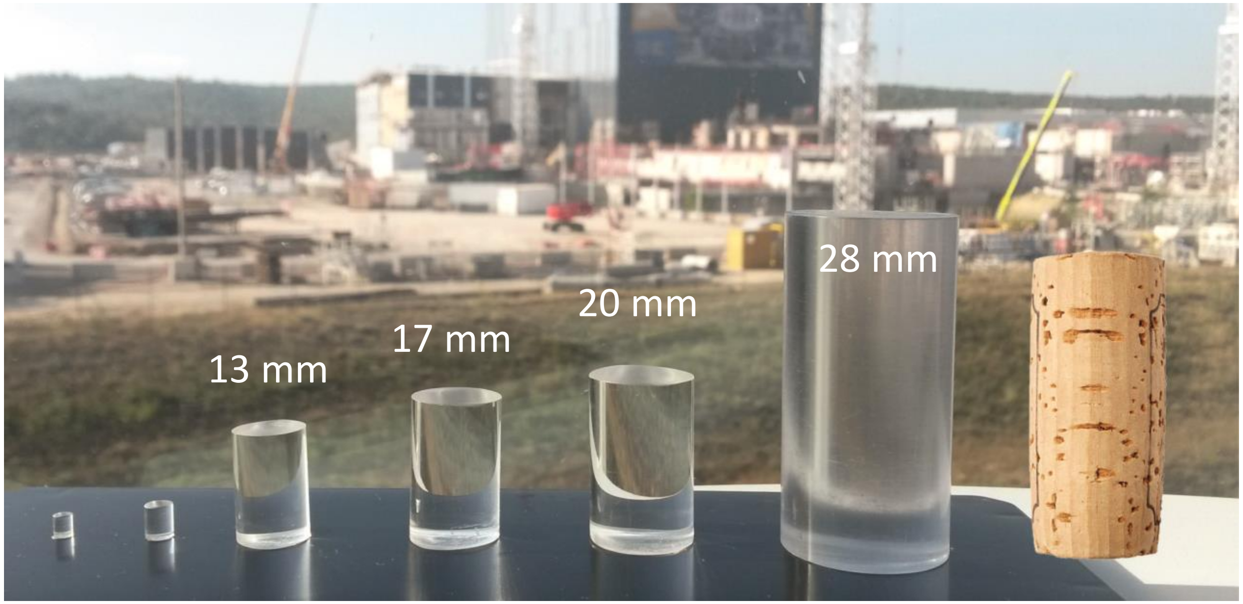
Implementation of 4 injectors

Each with 4 barrels



Long flight tubes require non-gaseous injection

Pellet sizes and quantities



×3 ×4 ×4 ×14

Pellet speeds:
150-500 m/s

Reaction times:
~10 - 30 ms (EP)
~16 - 55 ms (UP)

Required (assimilated)

$1x10^{25}$	*D_2*	*$3x10^{24}$*	*D_2*	***RE avoidance***
$1x10^{25}$	*Ar*	*$> 10^{25}$*	*Ar*	***RE energy dissipation***

		$5x10^{21}$	*Ne*	***halo currents***
$2x10^{24}$	*Ne*	*$5x10^{21}$*	*Ne*	***CQ heat loads***
$4x10^{22}$	*Ne + $2x10^{22}$ D_2*	*$4x10^{22}$*	*Ne*	***TQ heat loads***

ELMs
Fuelling

Main outcome of the discussion on the DMS design and concept

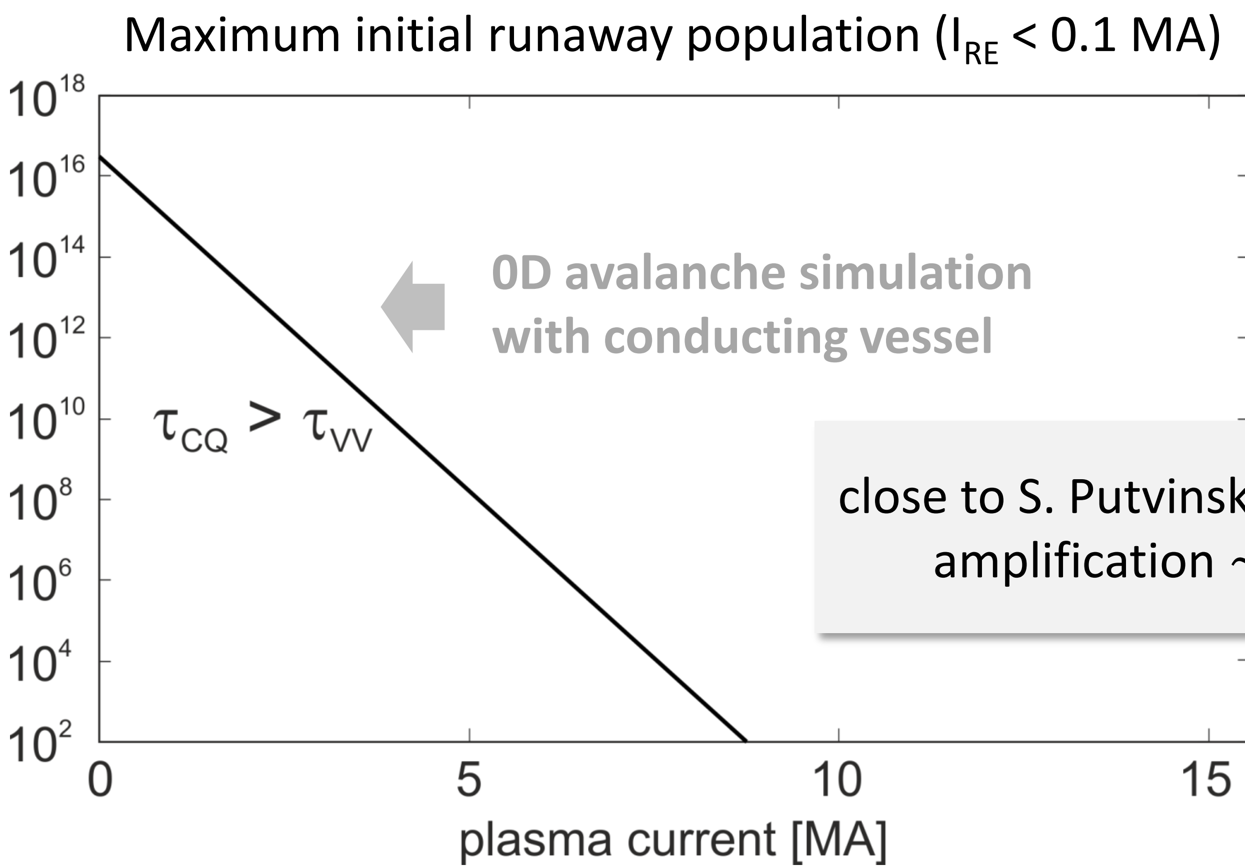
- *Hybrid option* for the DMS (MGI and SPI), as well as the in-port plug MGI valve planned for the non-active phase of operation are not essential and could be dropped (not fully unanimous).
- The present capabilities do not include *redundancy* and do not allow both *RE suppression and mitigation* in the same pulse, based on present projections. Services (gas feed, cryogenic lines, etc.) would need to be available for possible DMS upgrades at a later stage.
- The DMS relies on *multiple injections*. The effectiveness of this scheme requires that all pellets arrive within the timescale of the TQ.
- The *injection angle* in the upper port plugs in the present design does not allow the pellet shards to be directed towards the plasma centre.
- Physics and engineering R&D is required to draw conclusions on the optimum *gas/shard composition* and to optimise the shattering process.

Key outstanding issues that were identified are

- Baseline ITER DMS concept: *avoidance or suppression of RE* during disruption mitigation *cannot currently be guaranteed* because of the present limitations in the physics understanding of RE generation and disruption mitigation processes, and the pending demonstration of the technical feasibility to inject and assimilate sufficient quantities of material before the thermal quench.

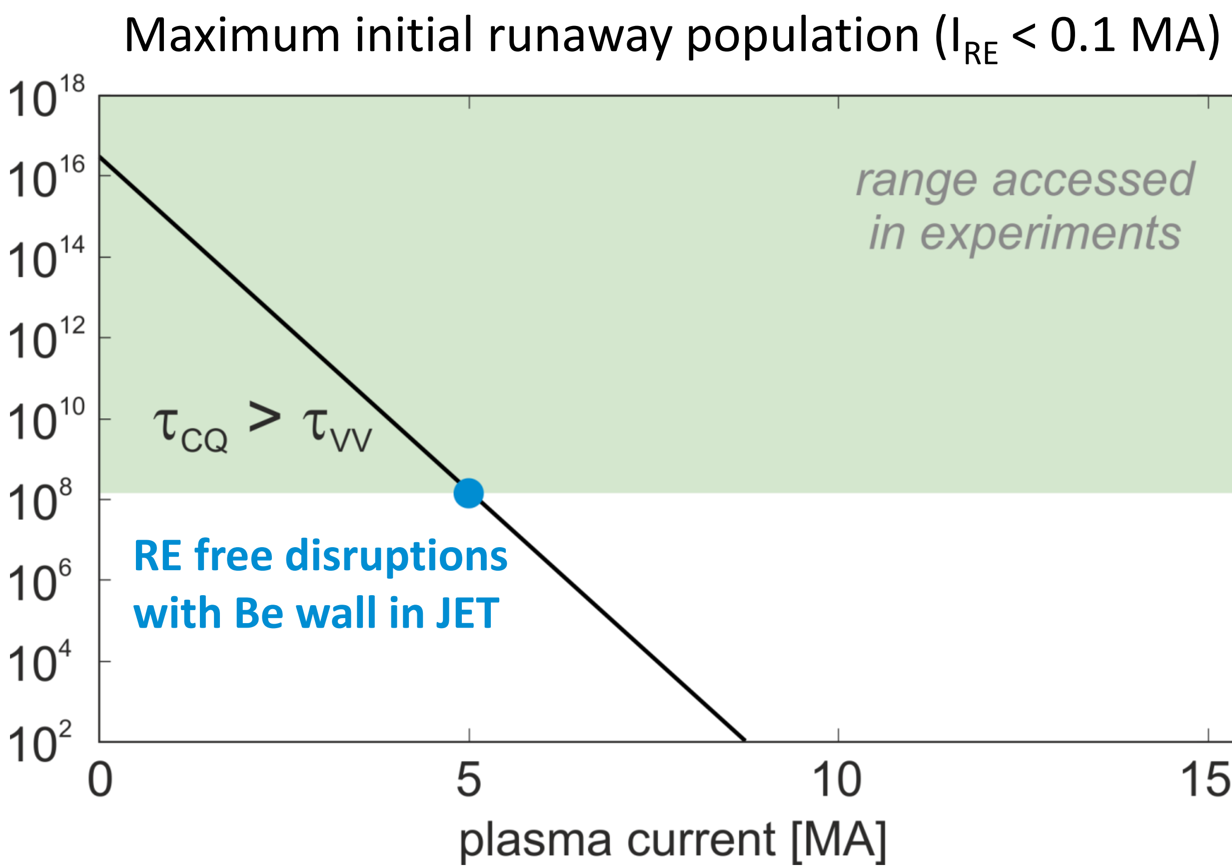
- A self-consistent scenario for *dissipation of a fully-formed RE plateau* as a second layer of defence *is not yet available*. The present experimental and modelling database, together with the constraints associated with the ITER environment, puts the feasibility of any scheme based on massive high-Z injection in question.

What is the initial runaway population that can be tolerated?



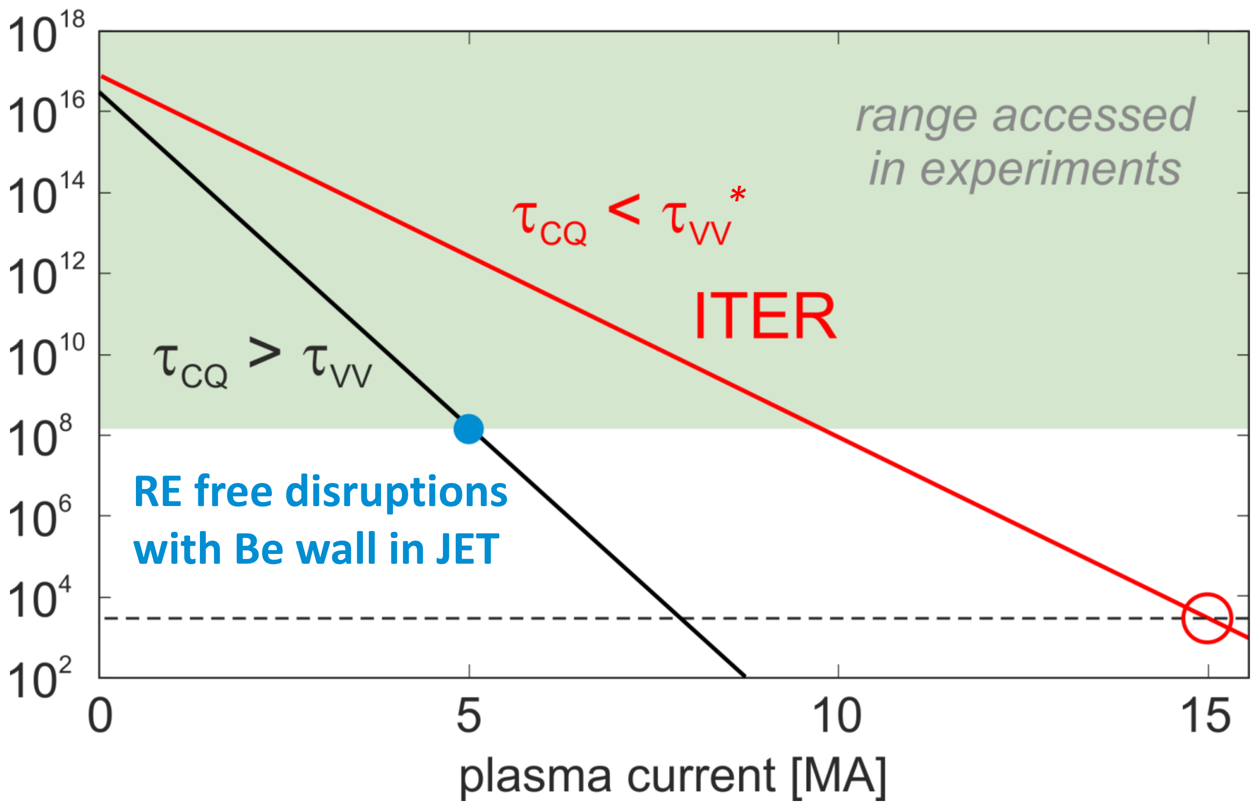
close to S. Putvinski, PPCF 1997:
amplification $\sim\exp(I_P)$

What is the initial runaway population that can be tolerated?



What is the initial runaway population that can be tolerated?

Maximum initial runaway population (I_{RE} < 0.1 MA)



ITER wall time about 0.5 s ➡ plasma current decay induces large vessel currents and avalanche is reduced

**assumption: loss of LCFS @ 10% initial I_P (significant margin to DINA results)*

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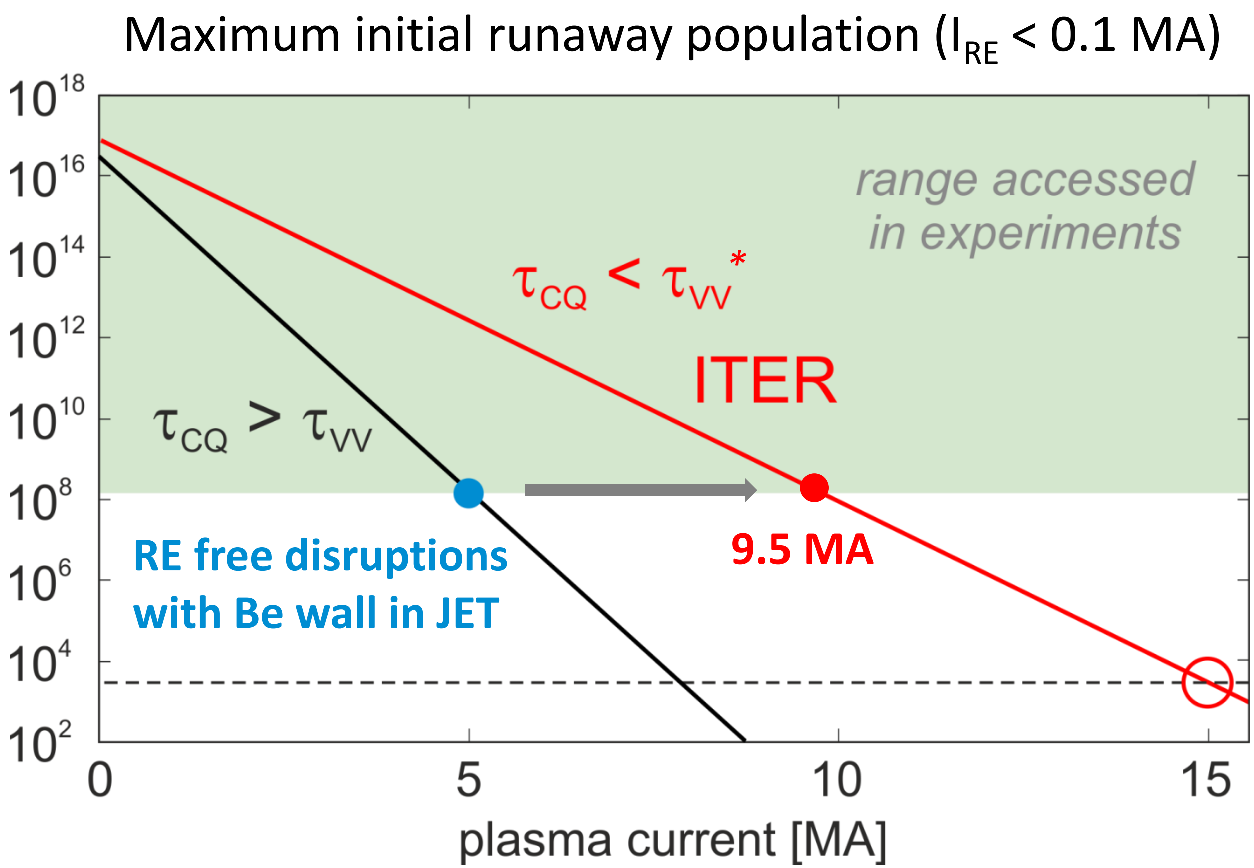

More runaway seeds can be tolerated with highly conductive vacuum vessel – to be further assessed in theory and experiment

assumption: loss of LCFS @ 10% initial I_P (significant margin to DINA results)

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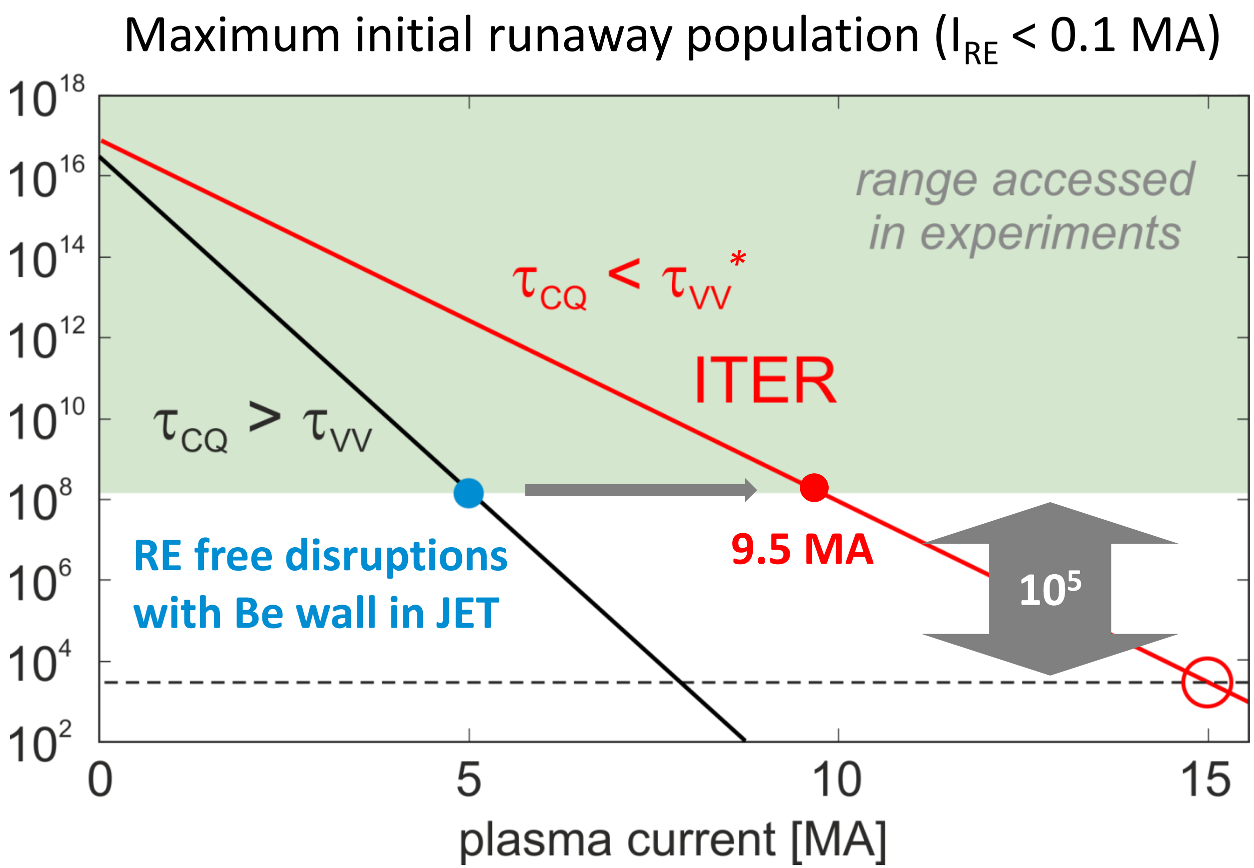
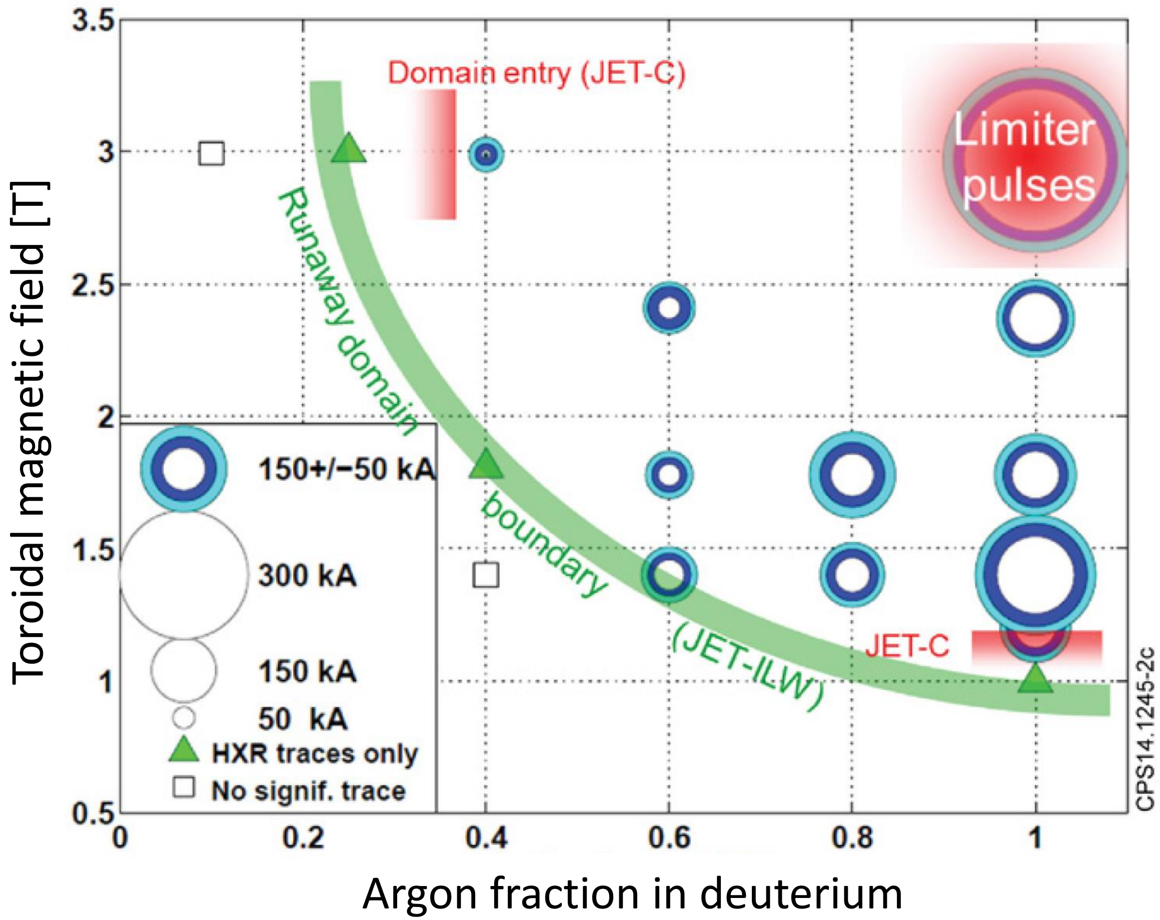


Runaway avoidance <u>not</u> confirmed for high current operation in ITER

**assumption: loss of LCFS @ 10% initial I_P (significant margin to DINA results)*

Runaways can be avoided with D_2 in JET

JET runaway domain with Ar/D_2 massive gas injection



C. Reux et al., Nucl. Fus. 2015

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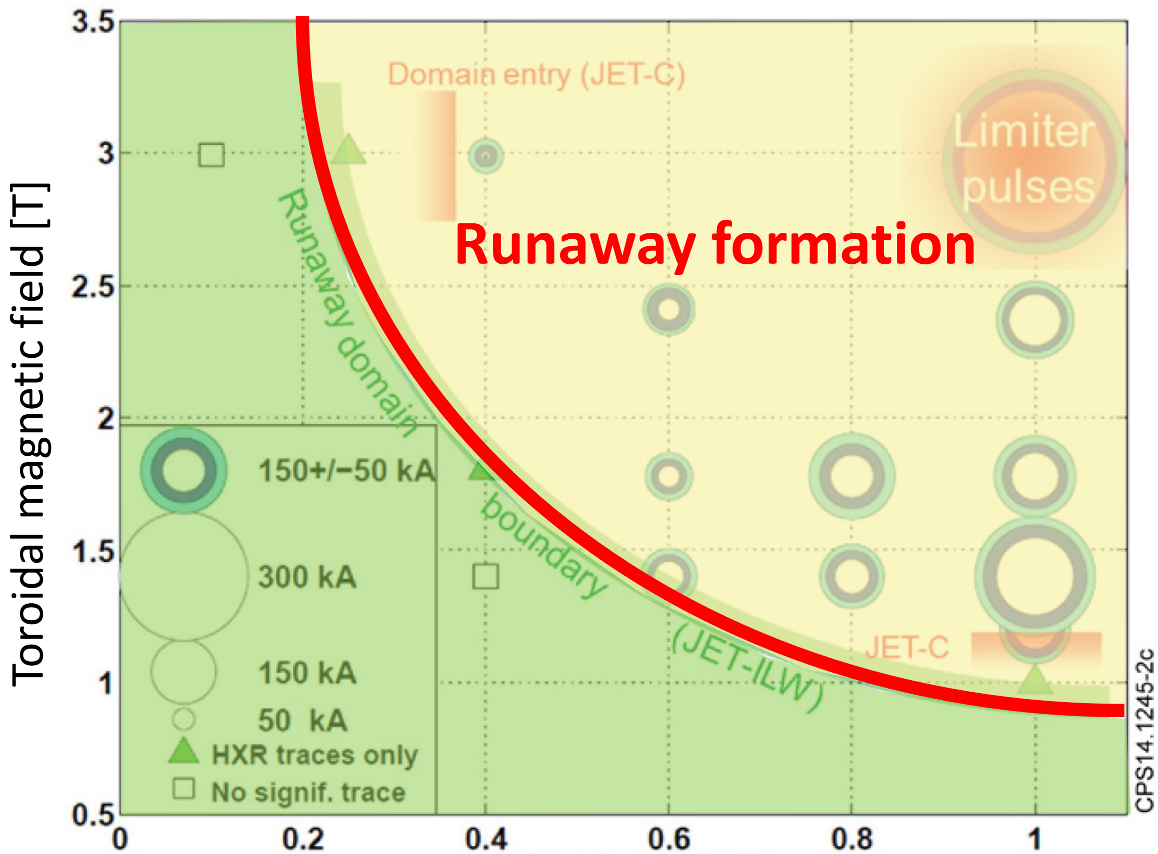
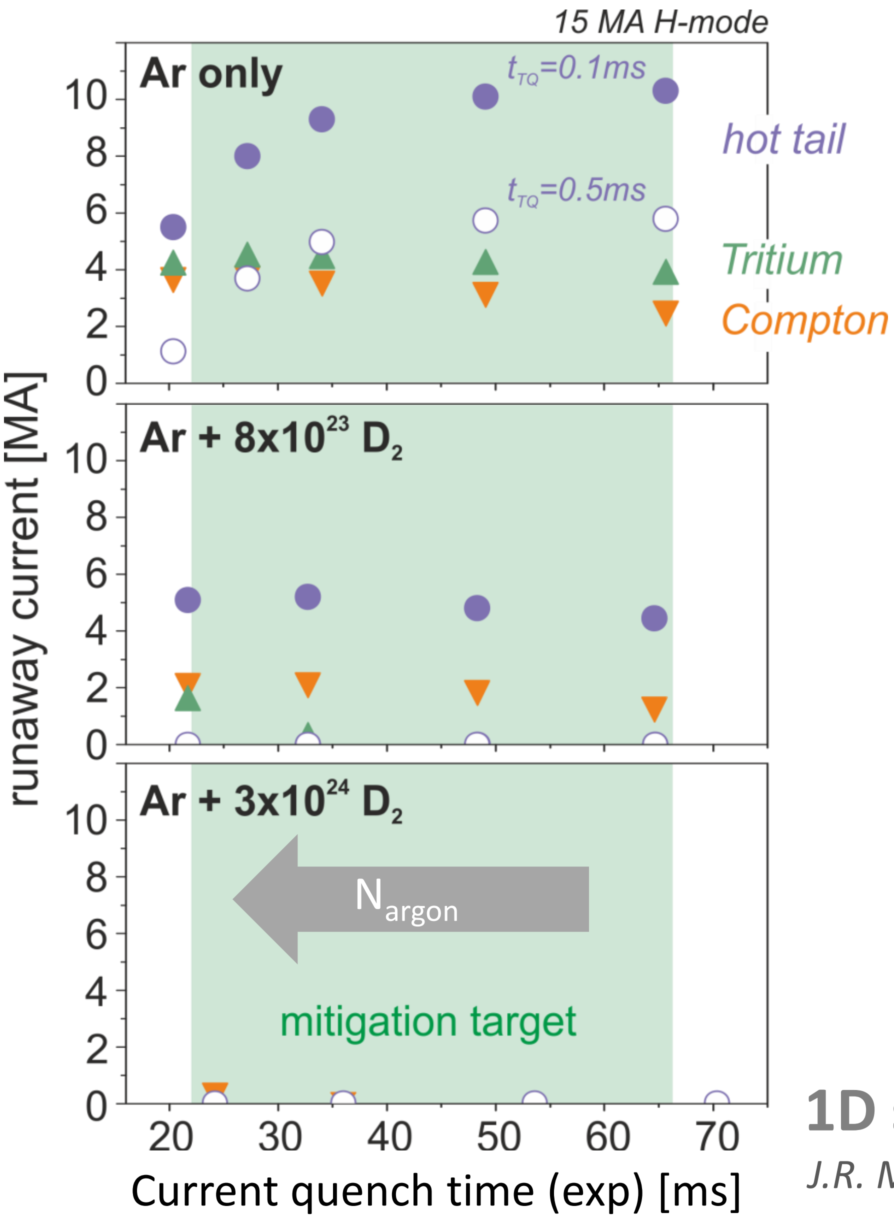


C. Reux et al., Nucl. Fus. 2015

JET mitigated disruptions are RE-free up to 3.25 MA with 90% D_2

Runaway Avoidance - Model predictions for ITER

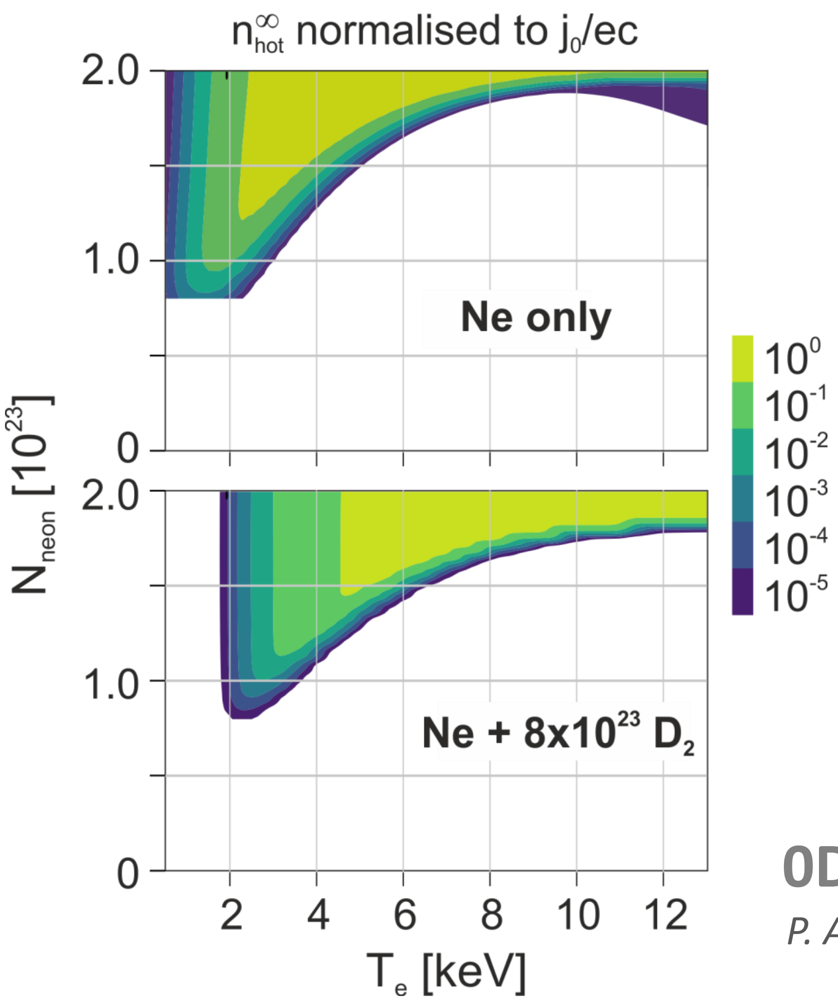


- First estimates of D_2 quantities for ITER
- Required quantities are high (density rise required overt the entire cross-section!)
- Hot tail model has no self-consistent thermal quench

1D simplified model

J.R. Martín-Solís et al., Nucl. Fusion 2017

Runaway Avoidance - Model predictions for ITER



- First estimates of D_2 quantities for ITER
- Required quantities are high (density rise required overt the entire cross-section!)
- Self-consistent thermal quench (energy loss through radiation) shows opposite trend with D_2 at high T_e

0D kinetic model (hot tail)

P. Aleynikov & B.N. Breizman , Nucl. Fusion 2017

Models are simplified and inclusion of the thermal quench MHD and self-consistent density and temperature evolution must be the ultimate goal

Model validation through experiments with D_2 admixture is urgently needed, e.g. test T_e dependence

IO workshop on Disruption Mitigation in ITER

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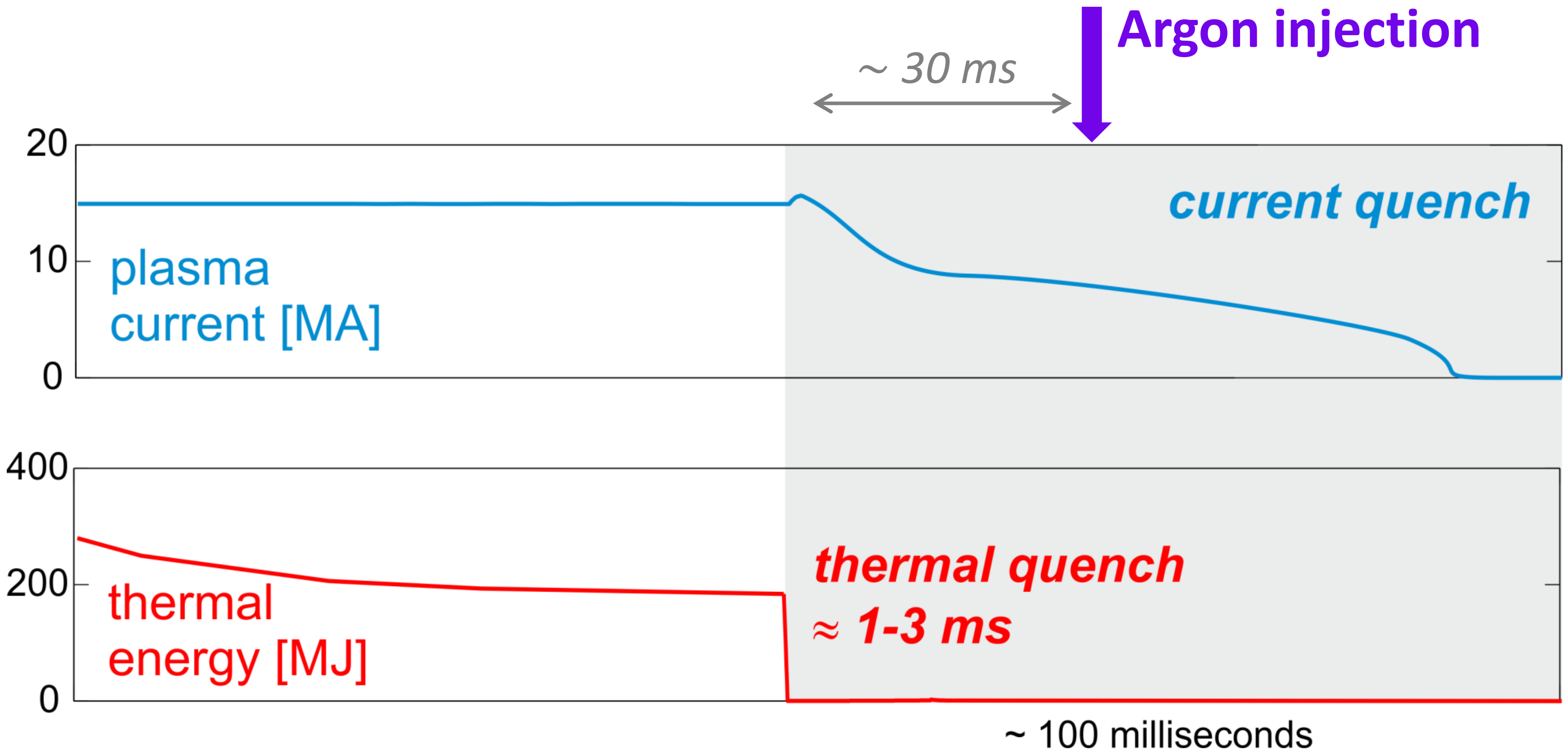
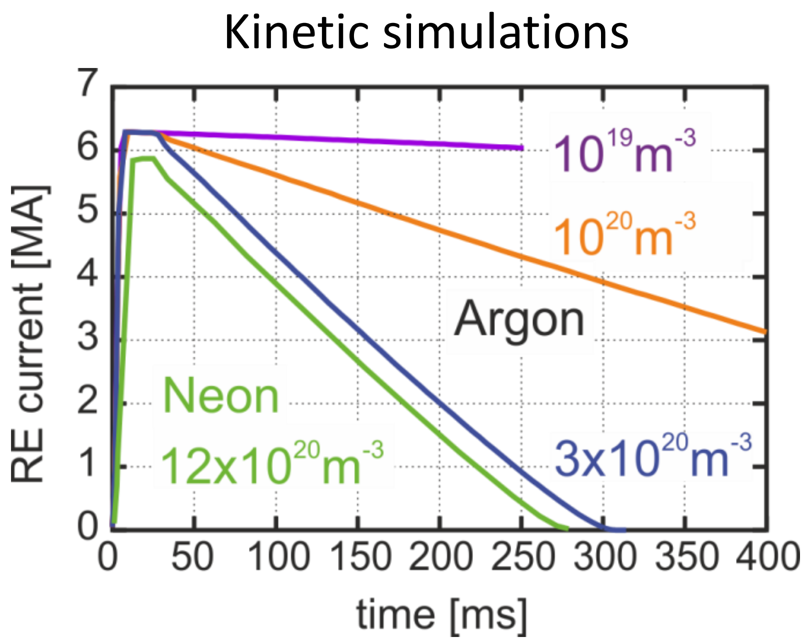
Dissipating Runaway Energy

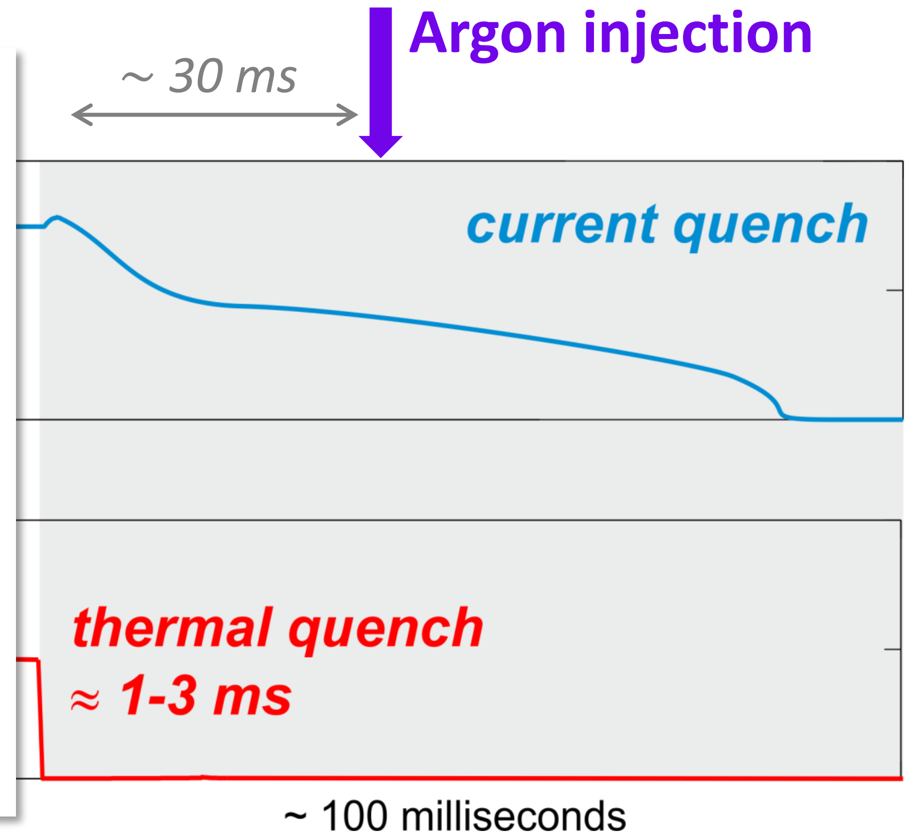


Pre-emptive injection for collisional dissipation of runaway energy

Dissipating Runaway Energy



P. Aleynikov, IAEA 2014

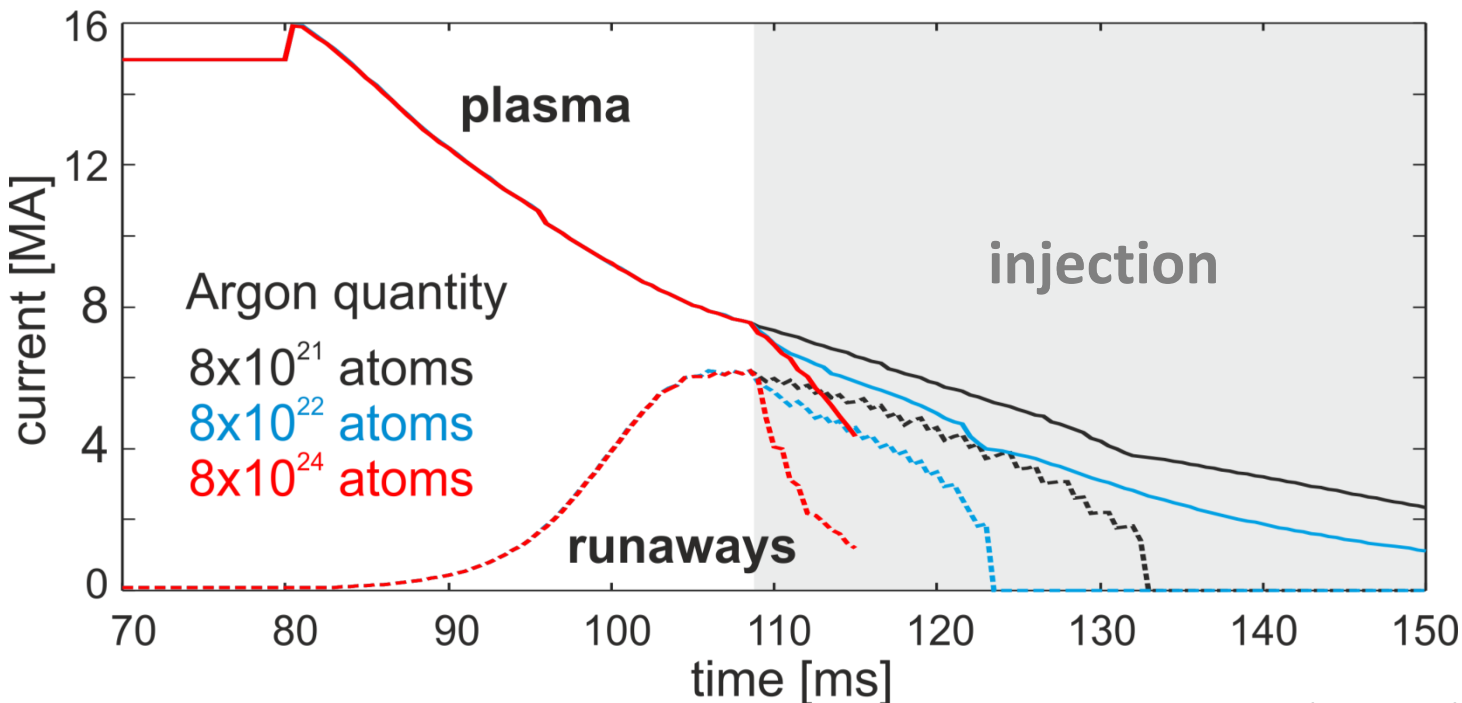


Pre-emptive injection for collisional dissipation of runaway energy

Dissipating Runaway Energy

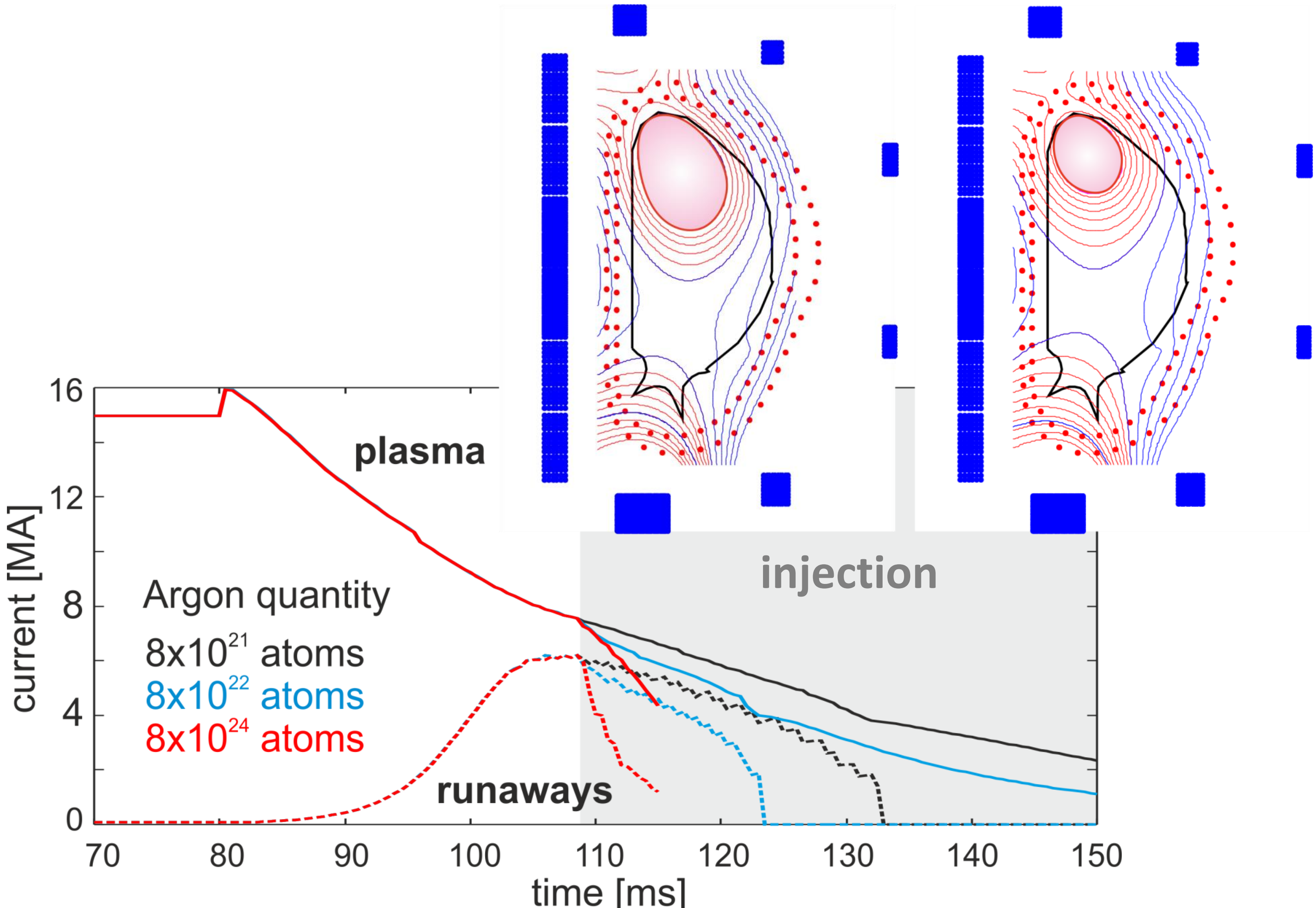
DINA simulation of runaway electron energy dissipation

(includes analytical expression consistent with kinetic simulation, P. Aleynikov, IAEA 2014)



S. Konovalov et al., IAEA 2016

Dissipating Runaway Energy



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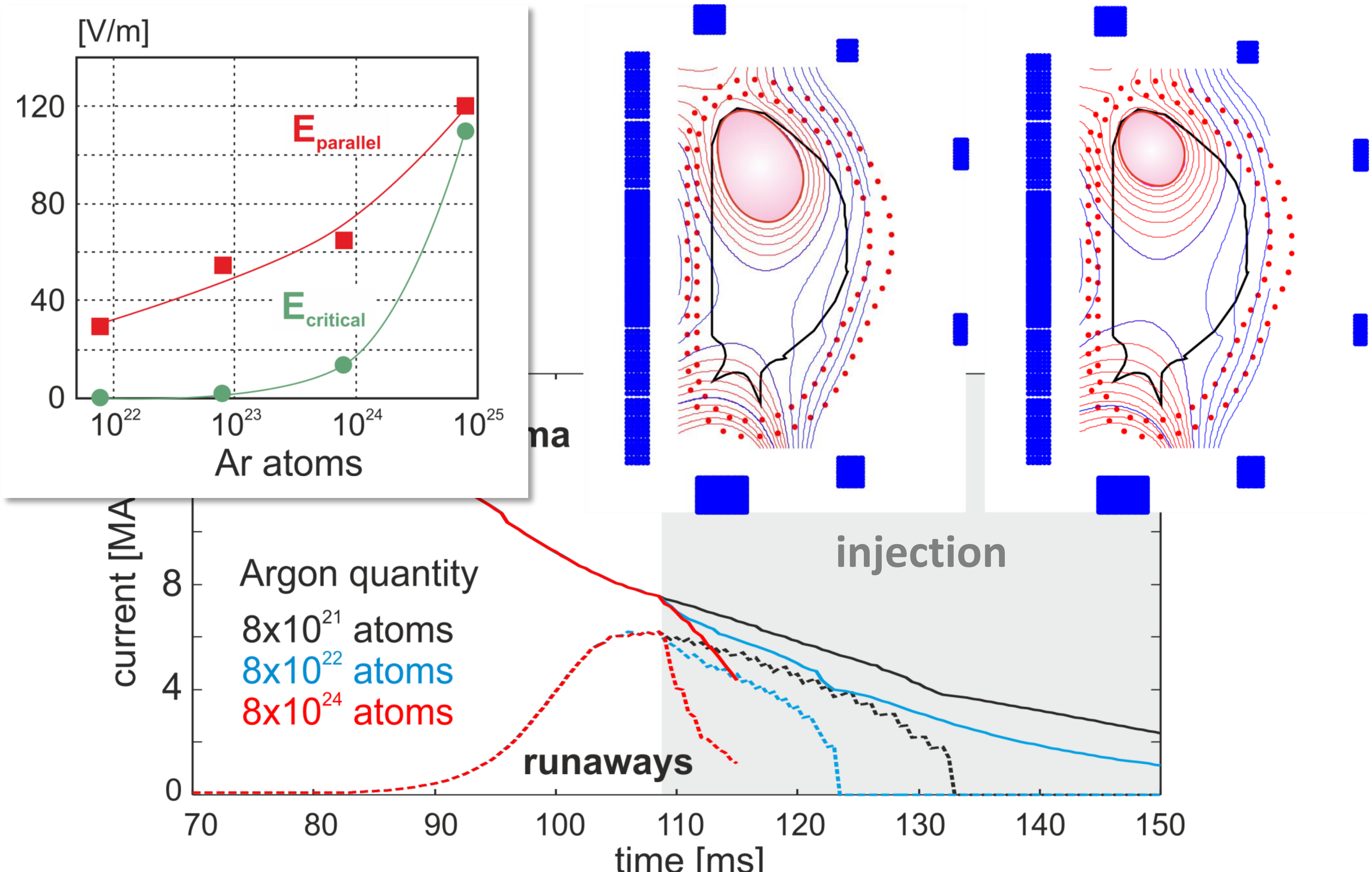
Dissipating Runaway Energy



S. Konovalov et al., IAEA 2016

Vertical displacement can cause additional electric fields through RE scrape-off (spatial distribution?)

DINA: energy dissipation requires large assimilated quantities

Low assimilation efficiency observed in experiments (updates this meeting!? DIII-D data suggests similar efficiency for SPI as for MGI)

IO workshop on Disruption Mitigation in ITER

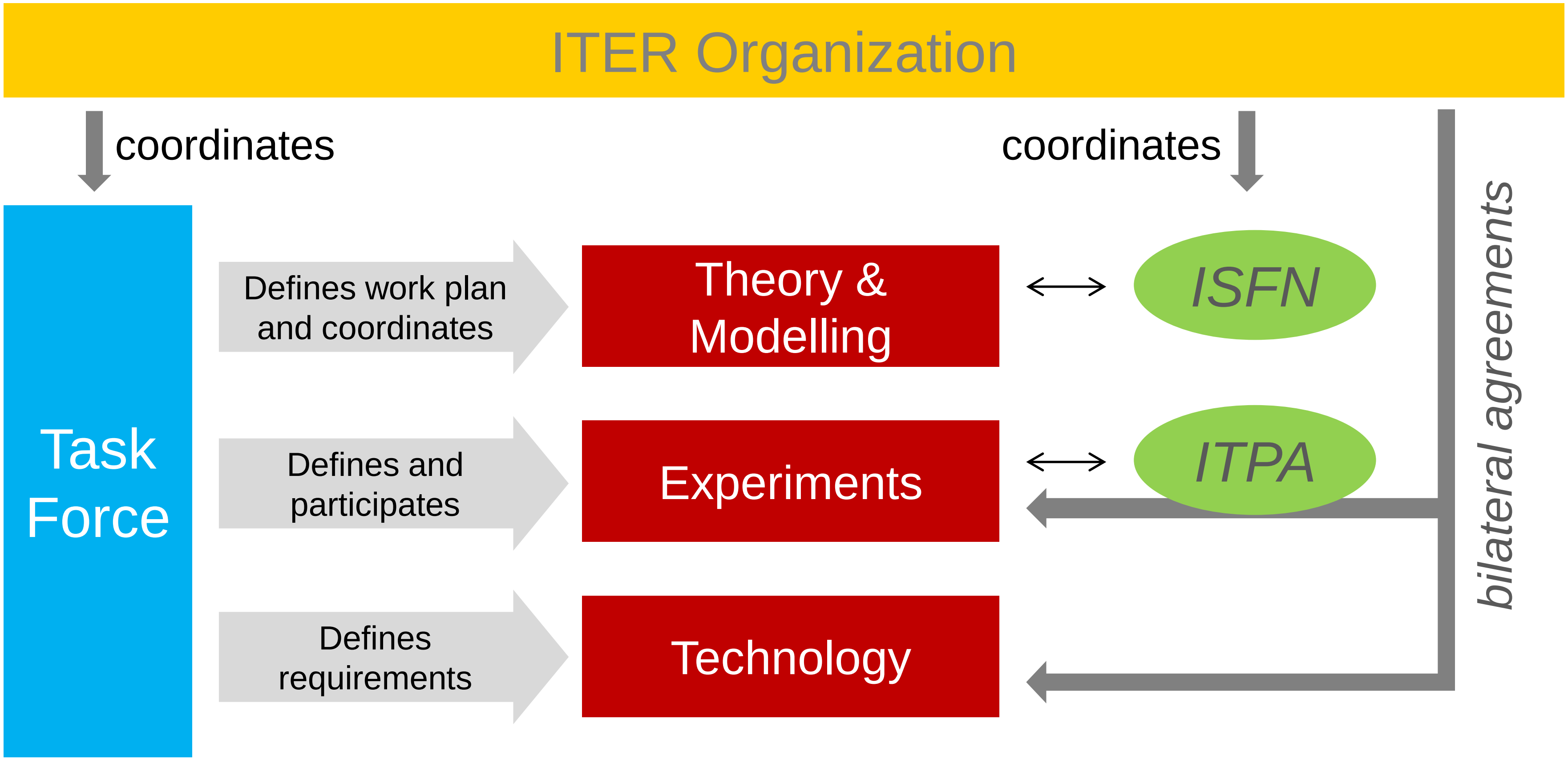
Key organisational issues

- The urgent need for an improved framework to strengthen the coordination of the IO needs in the field of disruption mitigation and the supporting R&D programs in the member states should be communicated to the ITER leadership.

- Many workshop participants emphasized the need the need for a highly focussed effort, led by the ITER project itself and implemented in the Members' fusion communities by the Domestic Agencies as the Members' representatives of the ITER project. Such an implementation framework should directly support the most urgent research needs and coordinate the efforts of the existing programs to answer the outstanding scientific questions most expeditiously.

Possible organisational structure

- Task force required for better coordination and involvement of the community
- Make use of existing frameworks/agreements as much as possible – a new agreement involving many parties will take years to become active



IO strategy for the DMS implementation

Baseline DMS

- Ready for 1st experimental campaign
- Timescale to finalise the design: 3 years
- But port plug integration happens already now
- R&D needs to be defined this year for design optimisation
- Experimental efforts at DIII-D and JET in 2017/18 will contribute

DMS+

- To be installed for 2nd experimental campaign (or later) if needed
- Timescale to finalise the design: ~ 8 years
- Likely material injection, but for example with improved injection technique
- R&D needs to be defined in the coming 2 years

Alternatives

- To be explored for risk mitigation, but present ideas are rare and/or require significant R&D to prove feasibility

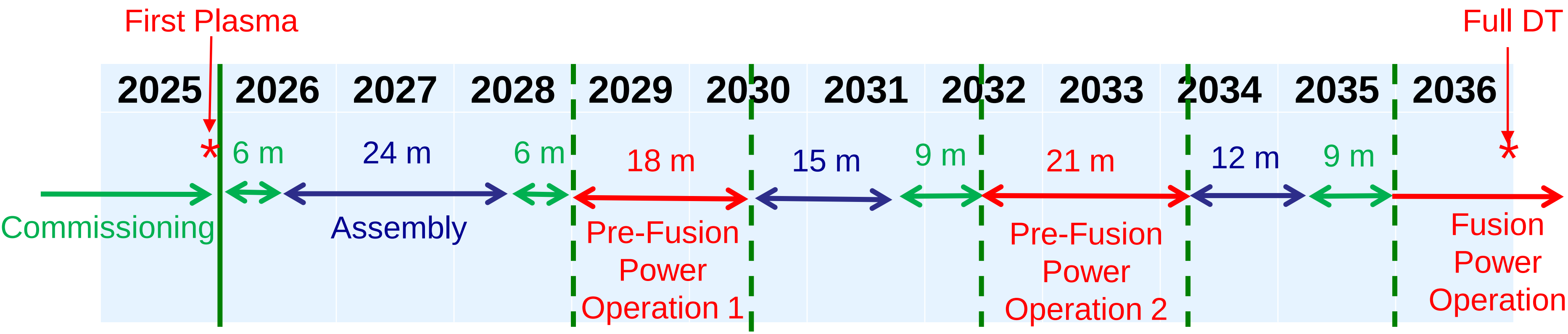
Risk: *Program delay if campaign milestones are not achieved due to insufficient mitigation capabilities*

Where we are and next steps

- Design and integration options for the baseline DMS are presently assessed and the R&D tasks to take decisions will be defined
- Risks of not achieving PFPO-1 or PFPO-2 objectives are assessed; Criteria: Runaway suppression (quantities, penetration,…), radiation asymmetries, quantities/assimilation for TQ and CQ mitigation

PFPO-1 objectives: L-mode, 7.5 MA (possibly up to 10 MA), $E_{th} \approx 30$ MJ
[optional H-mode, 5 MA, $E_{th} \approx 25$ MJ]

PFPO-2 objectives: L-mode, 15 MA, $E_{th} \approx 70$ MJ
H-mode, 7.5 MA, $E_{th} \approx 85$ MJ



Where we are and next steps

- IO Management is aware of the impact runaway formation will have on the exploitation of ITER and has been informed about the outcome of the workshop.

- *STAC-22 endorsed the ITER strategy to have SPI as the baseline DMS, but also communicated its concerns that the present design may not be able to mitigate runaways. It also recommends to establish an efficient framework and resource allocation for critical R&D.*

- IO will further detail its strategy to implement the new framework and will define a draft R&D work plan

- ITPA MHD group:
  next meeting focusing on disruptions, 9-11 October, F4E Barcelona
  - Asymmetric VDEs (model assessment and validation on request of IO)
    contact Vladimir Pustovitov
  - SPI: coordinate plans for experiments, DIII-D, JET(starting 2018), but also MST, HL-2A, JTEXT *contact Nick Eidietis*
  - RE energy dissipation scheme
    contact Michael Lehnen